(54) Title: LITHIUM NIOBATE OPTICAL MODULATOR
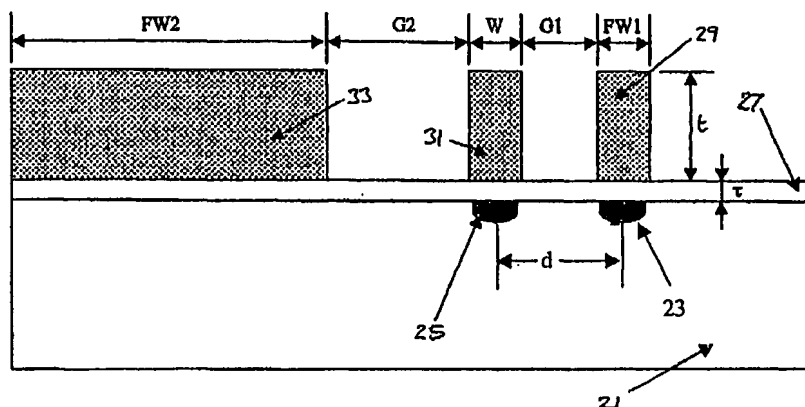
(57) Abstract: An optical modulator comprises a Z-cut lithium niobate substrate (21) on which is formed a Mach-Zehnder interferometer having two generally parallel waveguides (23, 25) lying beneath a buffer layer of dielectric material (27). First and second ground electrodes (29, 33) and a hot electrode (31) are disposed on the buffer layer (27), the first and second ground electrodes (29, 33) being spaced either side of the hot electrode (31), the hot electrode (31) and the first ground electrode (29) being proximate to at least apart of the respective waveguides (25, 23). The electrode structure is unsymmetrical in that (a) the hot electrode and the first ground electrode each have a width substantially less than that of the second ground electrode *and or* (b) the spacing between the first ground and hot electrodes is different from the spacing between the second ground and hot electrodes. whereby a range of chirp values can be obtained. When the spacing (G1) between the first ground and hot electrodes (29, 31) is smaller than the spacing (G2) between the second ground and hot electrodes (33, 31), and preferably the hot and first ground electrodes have a width not exceeding 15μm, the modulator is capable of operation at frequencies above 10GHz, possibly up to around 40GHz.

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

1
LITHIUM NIOBATE OPTICAL MODULATOR

This invention relates to lithium niobate optical modulators. In particular, the invention relates to lithium niobate optical modulators with electrode structures enabling chirp parameters to be chosen and controlled; some forms of the invention also achieve

5 operation at high frequencies (bit rates) of up to 40GHz.

As the demand for telecommunications services and bandwidth has boomed, the need for, and advantages of, external modulation in fibre-optic transmission systems has been firmly established. Lithium niobate is today one of the most important dielectric materials in the field of integrated optics, both for research and for technological

10 applications. This importance is due to the strong correlation between the optical properties of the crystal, its refractive index, and the application of various kinds of external fields; namely electric fields (electro-optic effect), sound waves (acousto-optic effect) and electromagnetic waves. Lithium niobate external modulators provide both the required bandwidth and a means for minimizing the effects of dispersion that limit system

15 performance.

Almost all lithium niobate optical modulators are travelling wave devices, in which the optical waveguide comprises a Mach-Zehnder Interferometer (MZI). High speed, broad bandwidth optical modulators are made by constructing a particular electrode structure on the buffer layer of the MZI modulator, which prevents light propagating through the

20 waveguide path from being absorbed by the electrode metal. MZI modulators usually operate with a push-pull electrode structure, so that fields of opposite polarity operate on each arm of the waveguide. These fields serve to change the index of the electro-optic lithium niobate, which in turn alters the phase of the light travelling in each waveguide, and thus allows operation of the interferometer. The optical phase or amplitude modulation

25 results from an interaction between the optical wave in the optical waveguide and the microwave wave guided by the electrode structure. Meantime, however, the refractive index of the lithium niobate also changes in response to exposure to light, including the light being modulated, producing changes that can be interpreted as phase modulation or as a change of frequency spectrum within the digital pulses, and which are known as "chirp". In an

30 idealised system operating with perfectly monochromatic light, chirp would be a defect to be minimised, but in a real system with a finite range of optical wavelengths, it is possible to exploit chirp to counter chromatic dispersion occurring elsewhere in the system, and so it is

desirable to be able to make modulators with pre-selected chirp values, preferably over a substantial range.

Lithium niobate MZI devices have the potential for very broadband operation, but they are limited by, inter alia, mismatches between optical and microwave effective

5   refractive indices (and hence mismatches between the velocities of the electrical and optical signals), electrode electrical losses, electrode impedance and drive voltage. Specifically, a velocity mismatch between the velocities of the electrical and optical signals together with electrical losses strongly curb modulator electro-optical response; high electrode impedance is needed to prevent reflections when the modulator is connected to a signal electrical

10   driver; and low driving voltages are a prerequisite. Introducing a very thin dielectric layer between the MZI structure and the electrodes can provide velocity matching between the electrical and optical fields, low electrical losses and high impedances, but requires higher driving voltages. Modulators made accordingly based on both X-cut and Z-cut lithium niobate substrates perform well up to 10GHz (the electro-optic effect in lithium niobate is

15   anisotropic and highest in the Z direction of the crystal's unit cell; to maximise the electric field in that direction and so the depth of modulation, waveguides in a Z-cut surface will normally be located directly below electrodes, whereas those in an X-cut surface will normally be located in the gap between two electrodes). For operation at frequencies in excess of 10GHz using the same driving voltage and microwave refractive index values,

20   Z-cut lithium niobate substrates enable lower electrical losses and higher impedances.

Typical electrode structures used for Z-cut lithium niobate MZI modulators include coplanar strip structures, as shown in fig. 1, having respective electrodes 1, 3 disposed on the buffer layer 5 directly above each of two parallel waveguides 7, 9 forming the MZI and having equal widths approximately the same as those of the waveguides. Such structures

25   provide high impedance, but also high electrical losses. Asymmetric coplanar strip electrode structures, as shown in fig. 2, are similar to the coplanar strip structures of fig. 1 except that the ground electrode 3 is much wider than the hot electrode 1. These structures present problems with electrical-optical signal velocity matching, which may be overcome by use of very thick gold electrodes (>30μm), though such thicknesses are difficult to obtain using

30   standard processes. Such structures also cannot achieve very low electrical losses suitable for high frequency applications, and their structure does not permit easy electrical connections to be made within a package.

Coplanar waveguide structures, as shown in fig. 3, are similar to asymmetric coplanar strip structures of fig. 2 with a second wide ground electrode 4 spaced symmetrically on the other side of the narrow hot electrode 1. These structures can provide good electrical loss characteristics, but to achieve optical-microwave effective refractive

5   index matching and high impedance requires an increase in buffer layer thickness which then requires higher driving voltages. One way to achieve optical-microwave effective refractive index matching and high impedance using a thinner buffer layer would be to use narrow ground electrodes. However, narrow electrodes suffer from very high electrical losses.

10   There remains a need for a Z-cut lithium niobate optical modulator design which is capable of operating at frequencies in excess of 10GHz with matching optical and microwave effective refractive indices, low drive voltage and electrode electrical losses, and high electrode impedance; some forms of the present invention solve this problem, as well as providing choice of chirp values at frequencies at present in use.

15   According to the invention, there is provided an optical modulator comprising a Z-cut lithium niobate substrate on which is formed a Mach-Zehnder interferometer having two generally parallel waveguides lying beneath a buffer layer of dielectric material. First and second ground electrodes and a hot electrode are disposed on the buffer layer, the first and second ground electrodes being spaced either side of the hot electrode, the hot electrode

20   and the first ground electrode being proximate to at least a part of the respective waveguides. The invention is characterized by an asymmetrical electrode structure in which

(a) the hot electrode and the first ground electrode each have a width substantially less than that of the second ground electrode

and/or

25   (b) the spacing between the first ground and hot electrodes is different from the spacing between the second ground and hot electrodes.

The hot electrode will normally have a width approximately equal to the width of the waveguide beneath it, and when option (a) applies, this is preferably also true of the first ground electrode; in this case, therefore, the widths of the hot electrode and the first ground

30   electrode will usually be substantially equal and not normally exceeding 15 μm. Preferably they will each have a width in the range 5-15 μm. The second ground electrode preferably has a width at least five times greater than that of the hot electrode (and usually the first ground electrode); more especially preferably at least ten times wider, in this context

considered an "infinite" width.

By adjustment of the two spacings between the hot electrode and the respective ground electrode, and/or of the widths of the three electrodes, a useful range of chirp values can be obtained, as will be illustrated below.

5   By use of a smaller spacing between the first ground electrode and the hot electrode than between the second ground electrode and the hot electrode, and preferably a first ground electrode with a width not exceeding 15μm, the inventors have been able to obtain a good match between the microwave and optical effective refractive indices, so maintaining low electrical losses and good impedance characteristics. This action does not affect the

10   driving voltage since neither the buffer layer thickness nor the spacing between the first ground and hot electrodes are adversely changed. Furthermore, by appropriate selection of geometrical parameters, it remains possible to provide a modulator structure with a residual chirp value close to zero (as an absolute value, irrespective of sign; as is understood in the art, only the magnitude of the chirp value is significant, because its sign can be reversed by

15   setting bias to chose operation on a part of the sinusoidal optical output intensity/driving voltage characteristic of the device that has negative or positive slope).

Preferably, the spacing between the first ground and hot electrodes is between 10 and 30μm and the spacing between the second ground and hot electrodes is larger, between 20 and 80μm.

20   Use of a (second) wide ground electrode in some preferred forms of the invention ensures low electrical loss, while the combination of this with a (first) narrow ground electrode ensures low driving voltage and high impedance. The narrow ground electrode further serves to reduce the microwave effective refractive index relative to the optical refractive index.

25   Preferably, the dielectric material comprises silicon dioxide with a thickness between 0:4 and 1.5μm, and the electrodes comprise gold having a thickness between 15 and 50 μm; thicknesses up to 30μm are easier to obtain with present electroplating techniques.

Additional features and advantages of the invention will be set forth in the detailed

30   description which follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the invention as described in the written description and claims hereof, as well as the appended drawings. It is to be understood that both the foregoing description and the following detailed description are merely exemplary

of the invention, and are intended to provide an overview or framework to understanding the nature and character of the invention as it is claimed.

The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings

5   illustrate one or more embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

Figs. 1 to 3 are sections through respective conventional coplanar strip, asymmetric coplanar strip and coplanar waveguide Z-cut modulator structures;

Fig. 4and 5 are section and plan views of a preferred modulator structure according

10 to the invention;

Figs. 6 and 7 are section and plan views of a second modulator structure according to the invention;

Figs. 8 to 11 are graphs showing the dependence of drive voltage, electrical loss, microwave index and impedance against ground electrode widths; and

15   Fig. 12 is a graph showing the dependence of residual chirp on electrode spacing in the modulator of Figs. 4 and 5.

A first preferred asymmetric coplanar waveguide modulator structure according to the invention, shown in Figs. 4 and 5, comprises a Z-cut lithium niobate substrate 21 with a thickness of around 500μm presenting an optical MZI on its surface. The MZI comprises a

20 mid section having two generally parallel waveguides 23, 25 which converge at either end into single input and output waveguides 22, 26. The parallel waveguides are formed in the plane of the surface of the substrate by a standard titanium diffusion process well known to those skilled in the art of modulator design. The axes of the parallel waveguides 23, 25 are 25μm apart and they have a depth of around 6μm and a width of around 10μm. A buffer

25 layer 27 of silicon dioxide having a dielectric constant of around 4 and a thickness of 0.65μm is grown by means of a conventional electron beam evaporation process directly on the surface of the lithium niobate substrate in which the waveguides 23, 25 are formed. Three parallel gold electrodes 29, 31, 33 are grown on the buffer layer 27 to a thickness of 27μm. Two of the electrodes 29, 31 are disposed directly above the parallel waveguides 23,

30 25 with a width of around 7μm. and a length extending to just short of the ends of the parallel sections of the waveguides 23, 25. The third electrode 33 is spaced 50μm from the middle electrode 31 with a width of 150μm and the same length as the other electrodes.

Using the middle electrode 31 as the hot electrode, the narrow electrode 29 to the

side of the hot electrode as a first ground electrode and the wide electrode 33 on the other side of the hot electrode 31 as a second ground electrode, the asymmetric coplanar waveguide modulator structure described has a chirp (alpha parameter modulus) value of about 0.05 (as further discussed below) and functions well at frequencies up to and

5   including 40GHz. The narrow first ground electrode 29 ensures that driving voltages may be kept low while maintaining high impedance. Fig. 8 shows the effect of increasing ground electrode widths on drive voltage, and fig. 11 shows the effect of increasing ground electrode widths on impedance for a conventional symmetric coplanar waveguide structure. The narrow first ground electrode 29 also serves to reduce the microwave effective

10 refractive index, enabling it to be brought down to match the optical refractive index, while still widening the space G2 between the second ground electrode 33 and the hot electrode 31 to benefit from low electrical loss and high impedance. Thus, the buffer layer may be kept within parameters for maintaining low driving voltages. The effect of increasing ground electrode widths on the velocity matching parameter is demonstrated graphically in fig. 10.

15 The wide second ground electrode 33 on the other hand ensures low electrical loss, as demonstrated in fig. 9; also such graphs are related to a conventional symmetric coplanar waveguide structure.

Table 1 provides a comparison between critical geometrical and performance parameters of the asymmetric coplanar waveguide modulator structure as shown in figs. 4

20 and 5 ("invention") and two coplanar waveguide modulator structures as shown in fig. 3, one with wide ground electrodes (CPW "inf") and one with narrow ground electrodes (CPW "fin"):

Table 1

Parameter	W (μm)	G1 (μm)	G2 (μm)	FW1 (μm)	FW2 (μm)	t (μm)
Invention	7	18	50	7	Inf	27
CPW "inf"	7	18	18	Inf	Inf	27
CPW "fin"	7	18	18	7	7	27

25

Parameter	τ (μm)	N_m	Z_0 (Ω)	EL(dB/cm) at 40GHz	V_π*L (V*cm)	$|\alpha|$ (chirp parameter)
Invention	0.65	2.15	50	2.45	11	0.05
CPW "inf"	0.65	2.21	34	2.5	11	0.66
CPW "fin"	0.65	2.11	41	3	10.7	0.32

where the geometrical parameters are as shown in fig. 4, N_m is the microwave effective refractive index, Z_0 is the impedance, EL is the electrical loss figure, and V_πL is the drive

voltage*electrode length product.

As can be seen, CPW "inf" gives a high microwave effective refractive index figure (2.21), while CPW "fin" has large electrical losses (3dB/cm). However, the structure according to the invention displays the advantageous electrical loss figure of CPW "inf" and

5   the velocity matching characteristics of CPW "fin" with high impedance and the same drive voltage.

In external modulators, chirp arises from phase modulation superposed on the modulated optical signal due to unequal modulation applied to the respective arms of the interferometer. If the integrals of the corresponding electrical and optical fields for the two

10 arms are not equal, a residual chirp arises. For X-cut modulators, the electrode structure is generally symmetrical with the optical waveguides positioned beneath the buffer layer but symmetrically between the electrodes so the relative driving voltages are the same. Provided there are no spurious effects, then no residual chirp is expected.

For conventional Z-cut modulator structures such as that shown in fig. 3, the

15 combined electrical and optical structure cross sections are asymmetric (though the electrode structure and the optical structure, considered separately, are each symmetrical), with the optical waveguides placed beneath the hot electrode and one of the ground electrodes. Typical expected driving voltage*electrode length products for such a structure would be 10-15V*cm and 70-100V*cm for the respective arms, with the integral of the

20 fields relating to the hot electrode arm being much higher than that relating to the other arm, leading to a fixed residual chirp. However, with the structure of the embodiment of the invention shown in figs. 4 and 5, the narrow ground electrode 29 over the waveguide 23 gives rise to driving voltages much closer to those exhibited by the coplanar strip structure of fig. 1, typically of the order of 15-25V*cm for the hot electrode arm and 20-30V*cm for

25 the ground electrode arm. Such close driving voltages lead to lower residual chirp than could be expected from the structures of figs. 3 and 2. Fig. 12 shows the effect that varying the spaces G1 and G2 between the hot electrode and the two ground electrodes in the structure of figs. 4 and 5 is calculated to have on residual chirp. For a fixed space G1, increasing G2 has the general effect of decreasing residual chirp. Conversely, for a fixed

30 space G2, increasing G1 has the general effect of increasing residual chirp. In particular, by properly managing the geometrical parameters of the structure in fig. 4, residual chirp values ($|\alpha|$) lower than 0.1 (usually considered to be a zero-chirp modulator) can be achieved.

In order to benefit fully from the respective advantages of the narrow and wide

ground electrodes as described above requires that the wide electrode be at least ten times wider than the narrow electrode, and the narrow ground electrode to be preferably the same width as the hot electrode.

Table 2 below summarises a series of modulator designs, all in accordance with
5   Figures 4 and 5, designed for operation at frequencies at present in operation (say 10GHz) and for various different chirp values. Throughout the series, the hot electrode and first ground electrode each had a width of 8 μm and the second ground electrode at least 80 μm ("infinite"), and the electrodes were 10 mm long and about 20-25 μm thick.

In the table, d is the distance between the axes of the two waveguides, G1 the
10 spacing between the hot electrode and the first ground electrode, G2 the spacing between the hot electrode and the second ground electrode, and τ the thickness of the buffer layer, all as shown in Figure 4. V_π is the drive voltage (which, since the electrode length is 10 mm, is numerically equal to the driving voltage*electrode length product). Chirp is tabulated as modulus (that is without its sign).

Table 2

d	G1	G2	τ	V_π	Chirp ($|\alpha|$)
22	14	6	0.55	9.63	0.45
		10	0.55	9.78	0.29
		14	0.55	9.85	0.21
		18	0.55	10.03	0.16
		26	0.6	10.45	0.10
		34	0.6	10.50	0.07
		42	0.6	10.53	0.05
26	18	6	0.55	9.80	0.51
		10	0.55	10.10	0.37
		14	0.55	10.20	0.27
		22	0.55	10.40	0.17
		30	0.65	11.60	0.12
		38	0.65	11.13	0.09
		46	0.65	11.13	0.06
32	24	8	0.6	10.53	0.52
		12	0.6	10.68	0.38
		16	0.6	10.95	0.29
		24	0.7	11.75	0.19
		32	0.75	12.10	0.14
		40	0.75	12.10	0.10
		48	0.75	12.15	0.07
43	35	10	0.7	11.83	0.54
		16	0.7	12.08	0.39
		22	0.7	12.20	0.29
		28	0.7	12.33	0.22
		35	0.8	13.10	0.17
		42	0.8	13.40	0.13
		50	0.8	13.20	0.10

Figs. 6 and 7 show an alternative asymmetric coplanar waveguide structure according to the invention in which the second ground electrode is the same width as the other two electrodes but the spacing of the electrodes is unequal. This structure achieves low driving voltages and high impedance, but it does suffer from higher electrical loss than the
5   structure of figs. 4 and 5.

Any discussion of the background to the invention herein is included to explain the context of the invention. Where any document or information is referred to as "known", it is admitted only that it was known to at least one member of the public somewhere prior to the date of this application. Unless the content of the reference otherwise clearly indicates, no
10 *admission is made that such knowledge was available to the public or to experts in the art to which the invention relates in any particular country (whether a member-state of the PCT or not), nor that it was known or disclosed before the invention was made or prior to any claimed date. Further, no admission is made that any document or information forms part of the common general knowledge of the art either on a world-wide basis or in any country*
15 *and it is not believed that any of it does so.*

Claims

1. An optical modulator comprising a Z-cut lithium niobate substrate on which is formed a
    Mach-Zehnder interferometer having two generally parallel waveguides lying beneath a
    buffer layer of dielectric material, and first and second ground electrodes and a hot
5   electrode disposed on the buffer layer, the first and second ground electrodes being
    spaced either side of the hot electrode, the hot electrode and the first ground electrode
    being proximate to at least a part of the respective waveguides, characterized by an
    asymmetrical electrode structure in which
        (a) the hot electrode and the first ground electrode each have a width substantially
10   less than that of the second ground electrode
        and/or
        (b) the spacing between the first ground and hot electrodes is different from the
        spacing between the second ground and hot electrodes.

2. An optical modulator according to claim 1 wherein the hot electrode and the first ground
15 electrode have widths approximately equal to the widths of the waveguides beneath
    them.

3. An optical modulator according to claim 1 or claim 2 wherein the hot electrode and the
    first ground electrode have substantially equal widths.

4. An optical modulator according to any one of claims 1-3 wherein the hot electrode and
20 the first ground electrode each have a width less than that of the second ground electrode
    and not exceeding 15μm.

5. An optical modulator according to claim 4 in which the spacing between the first ground
    and hot electrodes is smaller than the spacing between the second ground and hot
    electrodes.

25 6. An optical modulator according to any one of claims 1-4 wherein the second ground
    electrode has a width at least five times greater than that of the hot electrode.

7. An optical modulator according to any one of claims 1-4 wherein the second ground
    electrode has a width at least ten times greater than that of the hot electrode.

8. An optical modulator according to any one of claims 1-6, wherein the spacing between
30 the first ground and hot electrodes is between 10 and 30μm and the spacing between the
    second ground and hot electrodes is greater and between 20 and 80μm.

9. An optical modulator according to any preceding claim, wherein the dielectric material
    comprises silicon dioxide with a thickness between 0.4 and 1.5μm.

10. An optical modulator according to any preceding claim, wherein the electrodes comprise gold having a thickness between 15 and 50μm.
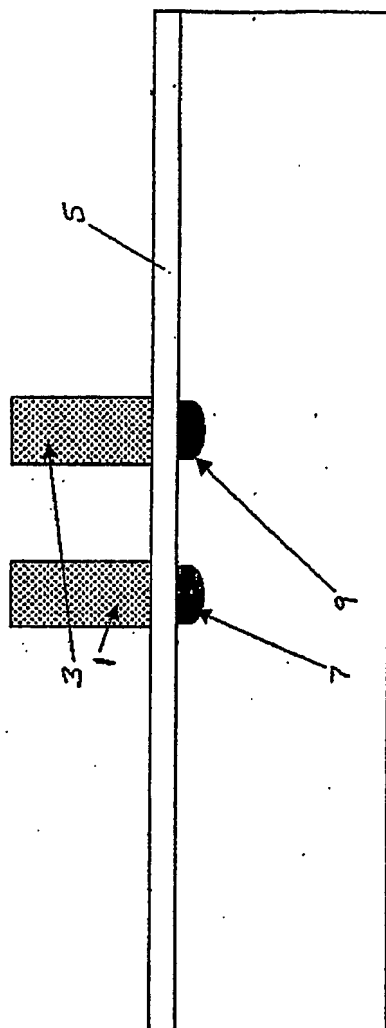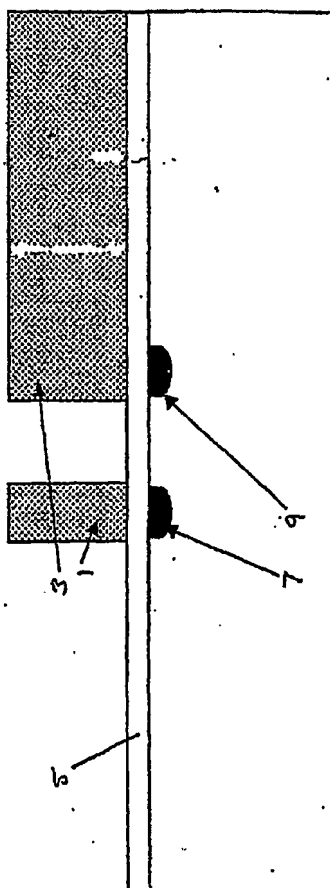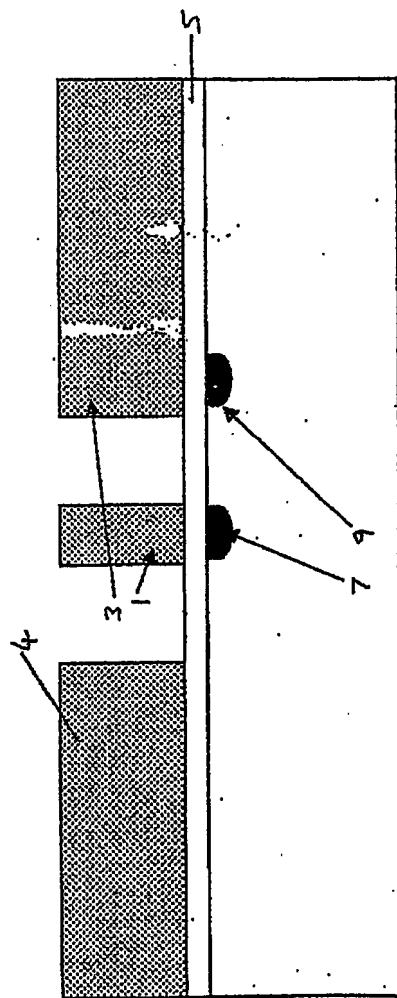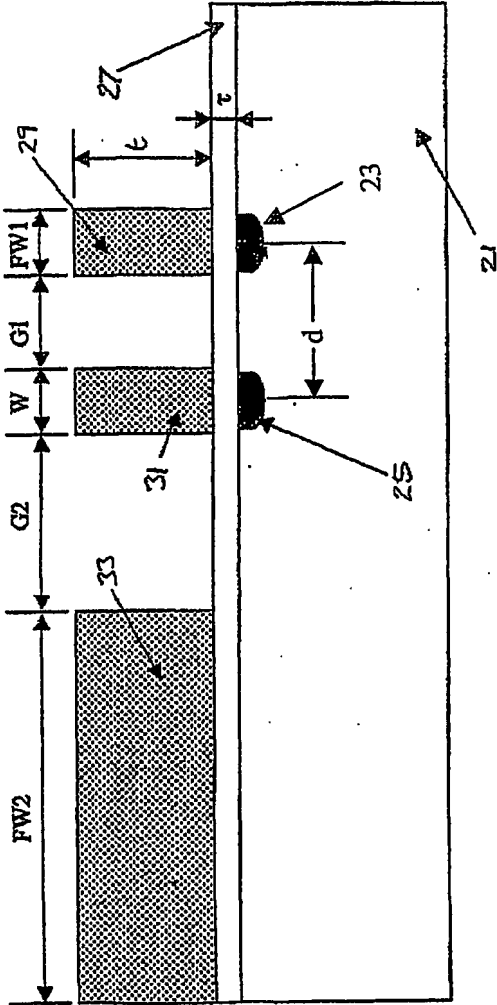
Fig. 1

Fig. 2

Fig.3

Fig 4
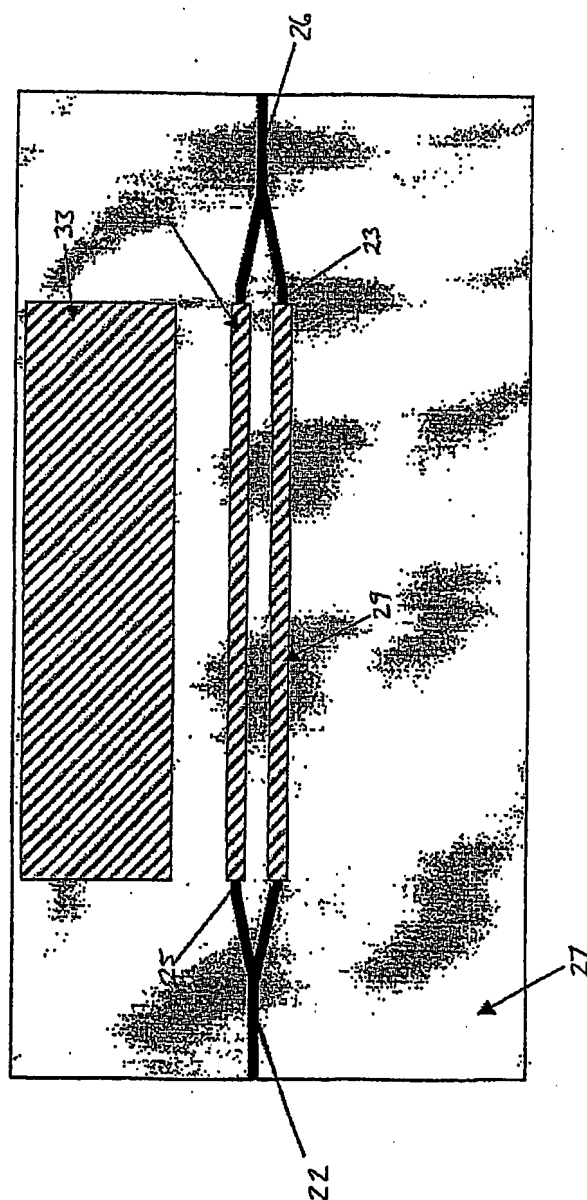
Fig. 5
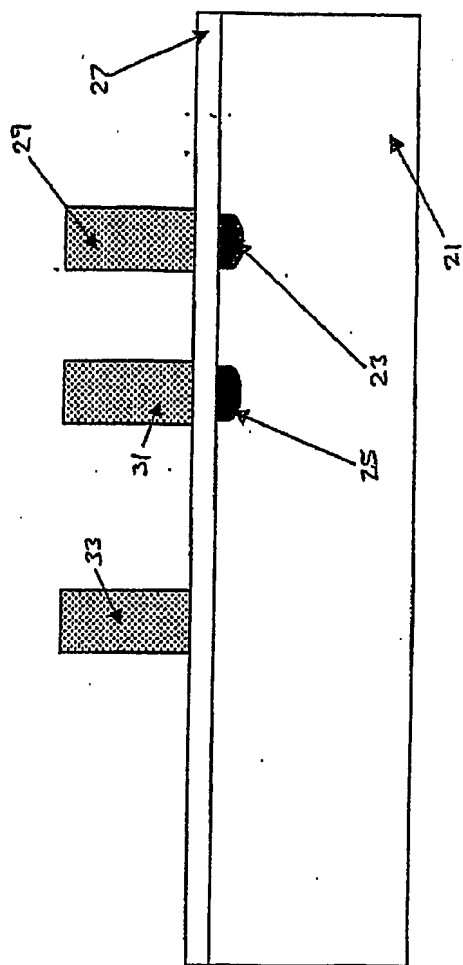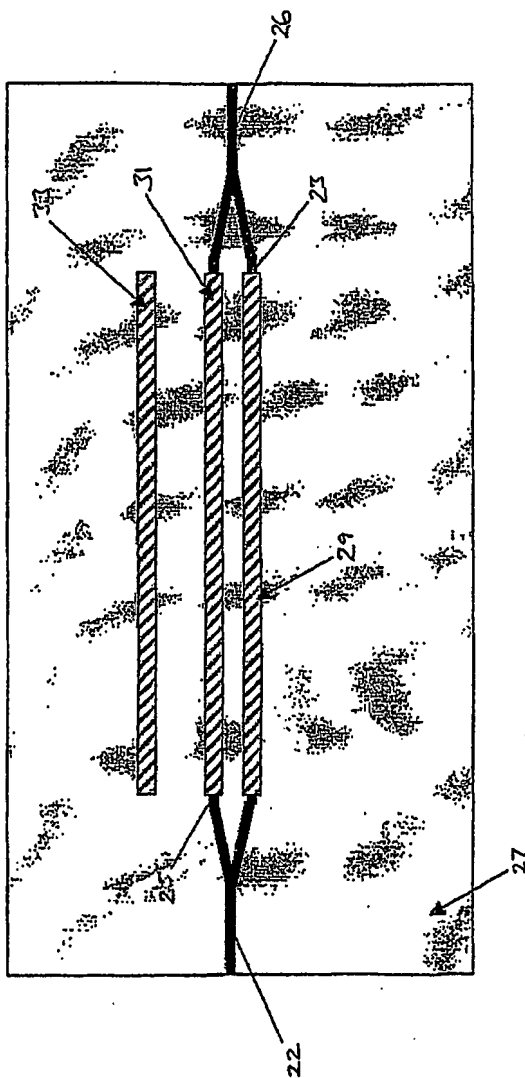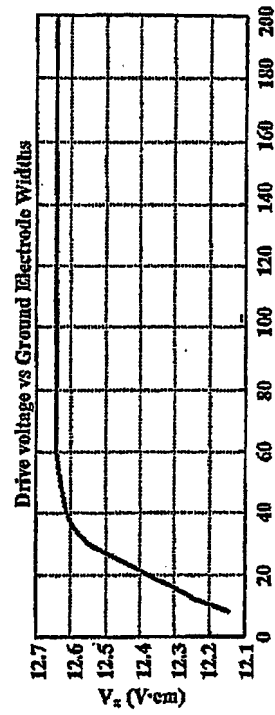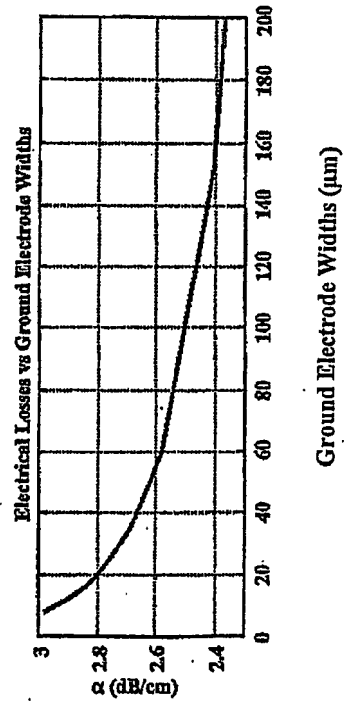
Fig. 6

Fig. 7

Fig 8

Fig 9
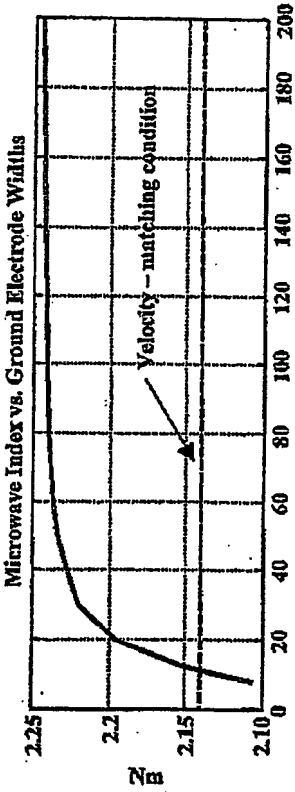
Fig. 10
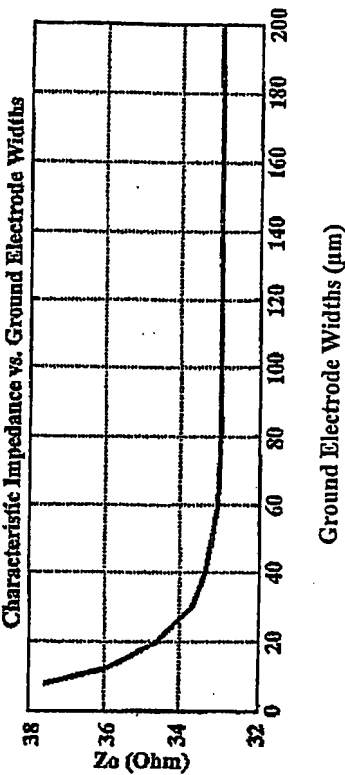
Fig. 11
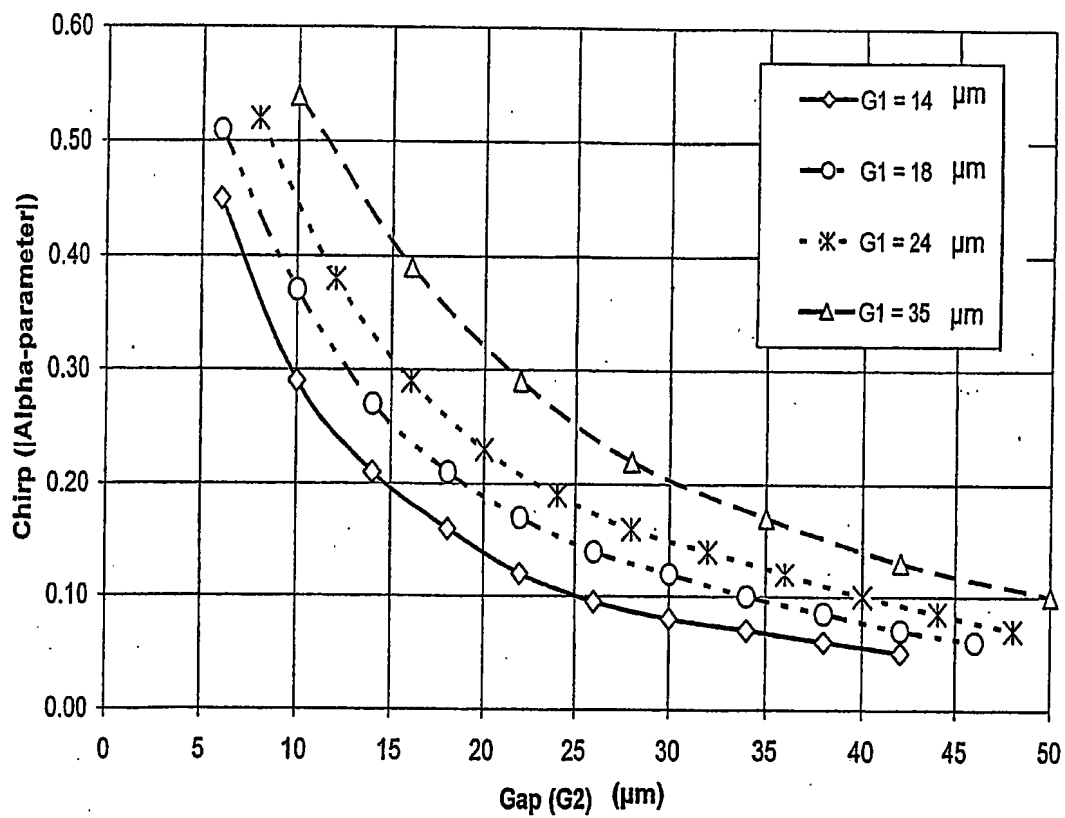
Residual Chirp

Fig. 12

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02F1/225   G02F1/035

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, IBM-TDB, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 813 092 A (SUMITOMO OSAKA CEMENT CO LTD) 17 December 1997 (1997-12-17) column 2, line 1 - column 2, line 40; figures 1A,1B	1
X	US 6 198 855 B1 (HUSSELL CHRIS ET AL) 6 March 2001 (2001-03-06) column 2, line 25 - column 8, line 9; figures 2,3	1
X	WO 96/36901 A (INTEGRATED OPTICAL COMPONENTS ; DONNELL ADRIAN CHARLES O (GB)) 21 November 1996 (1996-11-21) page 8, line 10 - page 9, line 30; figures 1A-2B	1

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| X | Further documents are listed in the continuation of box C. | | X | Patent family members are listed in annex. |

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search	Date of mailing of the international search report
10 February 2004	19/02/2004

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Kiernan, L

Form PCT/ISA/210 (second sheet) (July 1992)

6/19/2007, EAST Version: 2.1.0.14

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	NOGUCHI K ET AL: "MILLIMETER-WAVE TI:LINBO3 OPTICAL MODULATORS" JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE. NEW YORK, US, vol. 16, no. 4, 1 April 1998 (1998-04-01), pages 615-619, XP000768968 ISSN: 0733-8724 the whole document	1-10
A	TSUTOMU KITOH ET AL: "MODELING AND DESIGN OF TI:LINBO3 OPTICAL MODULATOR ELECTRODES WITH A BUFFER LAYER" ELECTRONICS & COMMUNICATIONS IN JAPAN, PART II - ELECTRONICS, SCRIPTA TECHNICA. NEW YORK, US, vol. 76, no. 1, 1993, pages 25-33, XP000395402 ISSN: 8756-663X the whole document	1-10

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